CIRP Journal of Manufacturing Science and Technology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

CIRP Journal of Manufacturing Science and Technology

journal homepage: www.elsevier.com/locate/cirpj

A design approach for safety based on Product-Service Systems and Function–Behavior–Structure

Leyla Sadeghi[a,*], Jean-Yves Dantan[a], Luc Mathieu[b], Ali Siadat[a], Mohammad Mohsen Aghelinejad[a]

[a] Arts et Métiers ParisTech, HESAM, Université de Lorraine, LCFC, F-57000 Metz, France
[b] École normale supérieure Paris-Saclay, LURPA, F-94235 Cachan, France

ARTICLE INFO

Article history:
Received 2 October 2015
Received in revised form 5 March 2017
Accepted 9 May 2017
Available online xxx

Keywords:
Design for human safety
Work situation
Product-Service System
Function–Behavior–Structure

ABSTRACT

Design for human safety is a complex issue because of the variability of human activities, machines and their environment as well as the variability of possible interactions between these components. The work situation is comprised of the means and the person(s) who act to carry out task(s) in a working environment in accordance with the conditions set for carrying out the task(s). The work situation can generate the hazardous conditions and undesirables events lead to harm. This paper deals with the work situation identifying and analyzing during design to improve safety. Product-Service System (PSS), which is an integrated combination of products and services that shift from product and service systems to Product-Service Systems has been used. The Function–Behavior–Structure (FBS), which covers behavior, is considered to include product and its utilization. The interaction between PSS and FBS, proposed in present paper, allows considering product behaviors and its interaction with service activities. This allows to distinguish the realization of functions by a product part, a service part or a combination of both. The analysis of this interaction is helpful for work situation analysis. Product and service behaviors modeling also are proposed in order to help this analysis. The applicability of the proposed approach is demonstrated through the application to the Power Take-Off (PTO) drive shaft.

Introduction

The main responsibility of making a machine safe lies in the design process [7]. In this context, the term “Design for Human Safety” (DfHS) captures this effort to integrate the knowledge on human safety in the design process [37].

The reviewing of the literature shows most of the publications on this subject have offered solutions that can be intervene quite late in the design process, often only on the detailed design phase, when significant decisions about product principles and structures have been taken. The most of methods that are used early in the design process, generally set constraints and are used to verify and validate. It should be highlighted the work conducted by Ghemraoui et al. [17,37]. Their proposition consists in a general suggestion for systematic risk identification and human-safety integration in the early design phase. The reviewing of the literature shows that use conditions are not or poorly taken into account during the design phase Houssin et al. [21] and there are always a gap between what is imagined in design and what is lived during the product utilization. Indeed, one of the most important sources of risk is linked to variety in work situation. To take into account this variety, idea is designing human behaviors performed in work situation in parallel with products, neither designing only products nor designing human activities.

These results demonstrate the growing importance of considering work situation as a core element of DfHS. The question then arises is: **How to integrate work situation into design process?** As mentioned previously, one of the most important sources of risk is linked to a divergence between expected working and real working. This demonstrates that the all the activities related to utilization of a system should be considered during design. The **work situation identifying and analysis** during design process allow overcoming this problem. Thus, it becomes more a question of **How to identify and analysis work situation during design process?** Whereas, the behavior describes how the system and its components perform [25], so this concept should be considered for

* Corresponding author.
E-mail addresses: sadeghi.leyla.87@gmail.com, leyla.sadeghi@ensam.eu (L. Sadeghi), jean-yves.dantan@ensam.eu (J.-Y. Dantan), luc.mathieu@ens-cachan.fr (L. Mathieu), ali.siadat@ensam.eu (A. Siadat), Mohammad-Mohsen.AGHELINEJAD@ensam.eu (M.M. Aghelinejad).

http://dx.doi.org/10.1016/j.cirpj.2017.05.001
1755-5817/

work situation analysis. Indeed, behavior refers to process or activity to be performed by product or human. So, we need a design theory which covers this concept. Thus, the question to be answered is **How to model the behaviors?**

The remainder of this paper is organized as follows. In Section "Research background and objective", terms related to DfHS and their definitions have been presented. This section, after description of a literature review on DfHS, presents the research objectives of present study. Section "Design for human safety based FBS and PSS" explains the proposed approach to integrate safety in the earliest design phases. In this section, work situation identifying and analysis have been described. In order to help this analysis, behaviors modeling are proposed. It helps decision making for selecting safer product behavior during design process. The effectiveness of the proposed approach is demonstrated in Section "Case study: Power Take-Off (PTO) drive shaft" by applying it to a Power Take-Off (PTO) drive shaft. Finally, the conclusions are defined in Section "Conclusions".

Research background and objective

Terms related to DfHS and their definitions

Human safety concerns accident prevention in work situations [36]. Work situation is comprised of the means and the person(s) who act to carry out task(s) in a working environment in accordance with the conditions set for carrying out the task(s). Service is described through the concept of activity. Regarding this any user activity performed in work situation then considered as a service. In our context, service could be defined as the utilization characteristics of user's product and all the activities related to this utilization. This concept includes addressing user's safety in work situation. Product is physical artefact to satisfy users' needs. System includes product and service. The work situation impacts on the human safety who works with/on/around of system which may contain hazard. If there is no hazard, there is no possibility of a hazardous situation and no possibility of presence of a danger for the system.

A hazardous situation exists when one or more persons are exposed to a hazard. If there is a hazard, a hazardous situation is possible. If there is no hazardous situation, there is no possibility of presence of a danger for the system. If there is a hazardous situation, we consider that the accident is always probable. In this case, a hazardous event is possible and there is possibility of presence of a danger for the system. Harm occurs as a result of a hazardous event. Risk is defined as an estimate of the probability of occurrence of this harm and its severity that could result. Probability is defined as an estimate of the probability of a hazardous situation occurring (exposure) and the probability of a hazardous situation leading to harm. Severity is defined as an estimate of the magnitude of harm. In producing the measure that becomes a statement of risk, it is necessary that determinations be made for the: existence of a hazard(s), exposure to the hazard, frequency of endangerment of that which is exposed to the hazard, severity of the consequences should the hazard be realized (the extent of harm or damage to people, property, or the environment) and probability of the hazard being realized. This risk which must avoided, eliminated, or controlled in the design and redesign processes of system which will result in improvement in the safety of human at work situation. This has been represented in Fig. 1.

As mentioned previously, the aim of the research presented in this paper has been to identify and analysis the work situation. For this aim, all the activities related to utilization of system should be considered during design. This aspect illustrates that the system functions and service activities should be integrated seamlessly from the early design phases.

Service part is described through the concept of activity. Regarding this any user activity performed in work situation then considered as a service. In our context, service could be defined as the utilization characteristics of user's product and all the activities related to this utilization. This concept includes addressing user's safety in work situation. The work situation analyzing allows formalizing this concept in the DfHS context with associating utilization and human activities.

Current industrial problems mainly concern the environment and the impact of mass production/consumption of artefacts [43,46]. One of the identified solutions is the concept of Product-Service Systems (PSS). A PSS is an integrated combination of products and services that shift from product and service systems to Product-Service Systems. The PSS is used in a broader sense, as a model to represent the defined "operating system" composed of interdependent product parts.

The concepts of product, service, system and work situation are redefined in the context of this research as:

- Product: physical artefact to satisfy users' needs;
- Service: utilization characteristics of user's product and all the activities related to this utilization;
- System: product + service;
- Work situation: is comprised of the means and the person(s) who act to carry out task(s) in a working environment in accordance with the conditions set for carrying out the task(s).

Let us take Power Take-Off (PTO) drive shaft, a means for transmitting rotary power from the tractor to the implement, as an example (Fig. 2). In PTO drive shaft, the movable shaft disengages from kinetic energy. Service is related to one or more activities which done by person on or around of PTO drive shaft. Whole of PTO drive shaft and the activity done by person near it constitute the system. When the PTO drive shaft is operating with missed, broken, damaged or poorly fitting safeguards and a person gets close to the PTO drive shaft, there is a potential "entanglement hazard". The operator may be in the vicinity of the source of kinetic energy. This system therefore presents a hazardous situation. A human may contact the source of kinetic energy. The PTO drive shaft therefore has a dangerous event.

Literature review on applications of DTM and DTT to analyze and identify work situations in DfHS

To improve human safety during design process, the large number of studies covering a wide variety of topics (e.g., [55,22,74,9,17] have been developed. Recently, Sadeghi et al. [78] provided a detailed analysis of the literature in order to identify literature trends and emerging research topics in DfHS. Fig. 3 shows the framework of DfHS. Risk and work situation are two aspects which must be considered for human safety. Applying design theories and methodologies (DTM) and design tools and techniques (DTT) help to integrate safety in design process. For more information on different DTM and/or DTT, the reader can refer to [51,66,69,31,44]. These papers classified or provided an overview of DTM and/or DTT.

The general principles of risk prevention in the work situation can be found through DTT. They focused in particular on the applications of DTM and DTT to analyze and identify work situations in order to improve human safety in manufacturing system design. Table 1 summarizes the results of analysis. Following DTM and DTT have been presented in this table: 'theory of inventive problem solving' (TRIZ), axiomatic design (AD), Function–Behavior–Structure (FBS), functional analysis (FA),

Please cite this article in press as: L. Sadeghi, et al., A design approach for safety based on Product-Service Systems and Function–Behavior–Structure, NULL (2017), http://dx.doi.org/10.1016/j.cirpj.2017.05.001